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Forecasting Research Division
Technical Report No. 173

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The relative utility of current observation systems to global-scale NWP forecasts; preliminary results

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Abstract

The utility of observations for Global NWP operations is assessed according to the frequency and significance of the benefits they deliver to 60-hour forecasts of pressure at mean-sea-level (PMSL). Results are based on eleven case studies which sample the most significant data impact events detected in routine operational forecasts, for Europe and North America, during the period September 1993 to May 1995.

All cases are classified as either North American, North Atlantic or North Pacific type according to the geographical location of the impact source. For each case, experiments are performed to find the smallest subset of data types required to deliver at least 90% of the benefit obtained when all data types are used. The data types which form this subset (referred to as the "90% subset") are then ranked in order of cumulative benefit. The benefit of a data type is assessed, over all cases, according to the frequency and significance of its inclusions in the 90% subset. Where an observation type reports more than one variable, each variable is assessed separately.

The main advantage of the case study approach is that observations are evaluated according to the benefits they deliver to forecasts of significant events, of prime importance to operational meteorology. A disadvantage of the method is that only benefits from the last 15hrs of data prior to the forecast are assessed. Consequently, observations which sample mainly the larger-scale part of the flow, which varies little on this time-scale, are penalised.

Preliminary results suggest that over North America the radiosonde and aircraft networks contribute most frequently, each having a similar number of inclusions as high ranking members of the 90% subset. Surface data and cloud-track winds provide the most important support roles. The North Pacific and North Atlantic cases show that aircraft winds contribute most frequently by a wide margin, with cloud-track winds and surface data occasionally playing key roles in these data sparse regions.

Initial comparison of the utility of wind and temperature data suggests that the benefit of wind profiles is equal to or greater than that of temperature profiles and that, in levels above ~400hPa, wind data are of more value than temperature data.

Preliminary results suggest that forecasts over Europe would benefit from more aircraft observations from North Atlantic and European routes and from climb and descent phases at airports. The need for more high-resolution data in low-to-mid levels over the Atlantic is emphasised. To begin to address this deficiency it is recommended that the feasibility of an "adaptive" observing system be investigated, and that the value of deploying more surface observations be given further consideration.

1. Introduction

An understanding of the relative utility of current observing systems to Numerical Weather Prediction (NWP) models is important to help make effective use of resources for observation. The benefit derived from current networks gives insight as to those which might be usefully extended and also helps determine priorities for proposed new systems.

In this work, observation utility has been evaluated according to the frequency and significance of benefits delivered to 60-hour forecasts of pressure at mean-sea-level (PMSL). Results are based on eleven cases which sample the most significant data impact events detected in routine operational forecasts, for Europe and North America, during the period September 1993 to May 1995.

The main advantage of the case study approach is that observation benefit is assessed according to the benefit delivered to forecasts of significant synoptic-scale events (e.g. cyclogenesis), which are of prime importance to operational meteorology. In contrast, the statistical approach, in which evaluation is performed over specific regions and periods, can result in important impacts on individual features being masked by negligible impacts during long "quiescent" spells. The lack of generality common to case study assessments is addressed by accumulating information over the eleven cases.

Only the impact of recent data, assimilated during the final 16 hours preceding the forecast, is assessed. The impact of earlier data, carried forward in the model background, is neglected. The method therefore places strong emphasis on evaluating the ability of observations to improve forecasts through specification of synoptic-scale phenomena (i.e. phenomena with Eulerian timescales comparable to 16hrs).

The impact derived from any observation is dependent on the assimilation methods employed. Results are therefore specific to the UK Met. Office assimilation scheme (for details see Lorenc et al; 1991), and may not always reflect the full potential of the observations. The NWP model used is the global configuration of the UK Met. Office's Unified Model (Cullen, 1992).

Details of the case selection method are given in section 2. The data impact experiments performed on each case and the method used to accumulate information over all cases are described in sections 3 and 4. Results on the utility of the various observation types, and an assessment of the relative utility of wind and temperature profiles are given in section 5. Conclusions and recommendations are given in sections 6 and 7.

2. Case selection and classification

This section contains some repetition of Graham (1994) so that the present report may be read without reference to the earlier.

2.1 *Selection*

The selection method is based on identifying cases in which recent data have had a marked impact on operational forecasts. This is achieved by looking for unusually large local differences in operational 72hr and 60hr PMSL forecasts, valid for the same time. Large differences indicate a significant data impact from the additional data assimilated prior to the 60hr run. Difference checking (and therefore

case selection) is limited to two areas where data density is relatively high, so that we may have reasonable confidence in the accuracy of the analysis used to assess the data impacts. The two areas are shown in Fig.1; the first incorporates much of North America, the second incorporates Europe and western Asia. Although each area includes some ocean, only forecast differences over land (as identified by the model land/sea mask) are considered.

Fig.1 The case selection areas over North America and Europe/Western Asia.

All cases for which the maximum absolute difference in forecast PMSL exceeds a predetermined threshold are short-listed for study. For the North American region the threshold was set at 20.0hPa, this resulted in a short-list of 21 cases out of a total of 885 forecasts during the period January 1994 to May 1995, representing the largest 2.4% of all data impacts (assuming there is some impact from recent data in all cases). For the European region the threshold was set at 12.5hPa, resulting in a short-list of 91 cases (representing the largest 10.3% of impacts).

Final selection is performed subjectively. Cases in which the two forecasts show marked differences in evolution, and where one forecast is significantly better than the other, are given preference. All the cases selected so far are examples of positive data impact, reflecting the fact that the 60hr forecast is usually superior to the 72hr forecast.

2.2 *Classification*

Each case is classified according to the geographical location of the impact source. This is achieved by tracing the impact back through the forecast to the assimilation phase. This classification allows us to keep sight of the role of coverage in data impact. For example, radiosonde ascents should deliver significant benefits more frequently to analyses over North America, where the network is relatively dense, than they will to analyses over the North Atlantic, where the network is very sparse. Cases are classified as being of either North American,

North Atlantic or North Pacific type - these regions broadly covering the initial location of systems which affect the case selection areas of North America and Europe some 2-3days later. In three of the eleven cases observations from two regions appear to have been involved in the impact; in these cases classification is made according to which region was considered (subjectively) to be the more important.

2.3 *Cases studied so far*

Eleven cases have been studied to date, comprising six North American cases, three North Atlantic cases and two North Pacific cases. The date of each case (identified by the verifying time of the T + 60 and T + 72 forecasts), and a brief description of the main feature improved in the T + 60 forecast are given in Table 1.

No.	DATE	LOC. AT ASSIM STEP	MAIN FEATURE IMPROVED IN THE T + 60 FORECAST
1	19:09:93	ATLANTIC	Low pressure trough over Mediterranean
2	26:10:93	N.AMERICA	East coast low
3	08:12:93	PACIFIC	Low over Western Canada
4	31:12:93	N.AMERICA	Suppression of spurious low affecting UK in T + 72 forecast
5	05:01:94	N.AMERICA	East coast low
6	21:01:94	ATLANTIC	Suppression of spurious low pressure trough over Denmark in T + 72 forecast
7	10:02:94	N.AMERICA	Low over east coast; high over Great Lakes
8	09:07:94	N.AMERICA	Low near Great Lakes
9	17:10:94	ATLANTIC	Suppression of spurious low pressure trough over western UK in T + 72 forecast
10	02:11:94	N.AMERICA	East coast low
11	03:11:94	PACIFIC	Low over NW Canada/Alaska

Table 1: Date and classification of the eleven cases studied. A brief description of the main synoptic feature improved in the T + 60 forecast is also given.

3. Approach

3.1 *General strategy*

Impact experiments are performed for each case to determine the data types which contribute "significantly" to the observed benefit. A data type is deemed to have contributed significantly if it is a member of the smallest subset of data types required to achieve at least 90% of the benefit obtained when all data types are used. The data types which form the subset (referred to as the "90% subset") are ranked in order of importance. The benefit of a data type may then be assessed according to the frequency and significance of its inclusions in the 90% subset.

Ideally, we would like the 90% subset to be unique; however, to ensure uniqueness we would need to assess the forecast skill obtained with all possible combinations of data types. Such an approach would require a great many model runs and is not a practical option. We have therefore adopted a simplified method in which the search for the 90% subset is guided by the benefit derived from each data type when used on its own in the assimilation (referred to as the "individual" benefit). The main assumption made is that the data type with the largest individual benefit will always be the most significant member of the 90% subset. The method is described in detail with the aid of an example case in section 4.

3.2 *Format of the impact experiments*

All experiments involve a 72hr integration of the global model initiated from a common analysis. For the first 16hrs the model is run in assimilation mode, during which the data whose benefit are to be measured are inserted. The UK Met. Office assimilation scheme uses a "nudging" technique in which observations are assigned maximum weight at the time of their validity. Observations valid for the first 15hrs of assimilation are inserted with "nudging" continuing for a further hour. The remaining 56hrs of integration are run in forecast mode (referred to nominally as a 60hr forecast from the last main synoptic hour of the assimilation period).

For each case two control experiments are run; one using all the available data (the ALL OBS run); and a dummy assimilation using no data (the NO OBS run). The ALL OBS and NO OBS runs, respectively, are equivalent to the 60hr and 72hr operational forecasts found to differ significantly by the case selection procedure. The benefit of the data to the PMSL forecast is measure according to the reduction in root-mean-square error achieved relative to the NO OBS control over an area enclosing the feature of interest. The evaluation area is chosen so that it encompasses the main regions of 60hr and 72hr forecast error - typically the area might include both the positive and negative poles of an error dipole associated with a poorly positioned depression.

3.3 *The data types assessed*

The individual data types assessed are shown in Table 2. Restrictions on the use of data within the model will clearly have an impact on the potential benefit, and are indicated in the table. Where an observation type reports more than one variable (e.g. radiosondes or aircraft reports) each variable is assessed separately.

No attempt is made to quantify the coverage of the data type, consequently a neutral individual impact from a given data type may mean that that data type was not represented in the vicinity of the system of interest. It is hoped that

OBSERVATION TYPE	ABR.	REMARKS ON GLOBAL MODEL USAGE		
RADIOSONDE WINDS	RsW	Includes PILOT reports		
RADIOSONDE TEMPERATURES	RsT	-		
RADIOSONDE HUMIDITIES	RsH	-		
AIRCRAFT WINDS	AcW	-		
AIRCRAFT TEMPERATURES	AcT	-		
SURFACE OBSERVATIONS	SFC	Over land: PMSL reports only Over ocean: PMSL and wind observations from some platforms		
SATELLITE TEMPERATURE SOUNDINGS	SaT	TOVS data: Form used = 120km and 500km NESDIS retrievals. Not used below 100hPa over land, or below 850hPa over sea (north of 30S)		
CLOUD-TRACK WINDS	CTW	Observations not used in Northern Extratropics (20-90N)		
			Before 2/8/84	After 2/8/94
		GMS	Above 500hPa	Below 500hPa (over land)
		METEO-SAT	Above 500hPa (over land)	Below 500hPa (over land)
		GOES	Above 500hPa (over land)	Below 500hPa (over land)
		INSAT	All	All
SCATTEROMETER 10M WINDS	SCT	-		

Table 2: Data types assessed and remarks on their use in the Global Model.

sampling problems such as this, which arise from the element of randomness in the distribution of the various data types relative to the features of interest, will be alleviated by the strategy of accumulating information over a number of cases.

4. Details of the method: an example case

In this section we describe the procedure for finding the data types which comprise the 90% subset. As an aid we shall refer to results from Case 10 - a cyclogenesis event which occurred over eastern Canada during November 1994 (Table 1).

4.1 *Assessing the individual impact of data types*

A model run is performed for each of the 9 data types shown in Table 2, in which only that data type is presented to the assimilation. For simplicity, and to ensure any downstream effects are captured, the data type is assimilated globally rather than locally in the region of interest. A table of the individual benefits of all data types is thus produced for each case. Individual benefits for Case 10 are shown in Table 3, with data types listed in order of decreasing benefit (i.e. increasing root-mean-square error).

Substantial individual benefits, ranging from ~30-50% of the benefit obtained with all the observations types (the "ALL OBS" benefit) were obtained with aircraft and radiosonde observations of wind and temperature. Only small benefits (7% or less) are derived from the sole use of surface data, radiosonde humidities or cloud track winds. Satellite temperatures are not used in the assimilation over land areas below 100hPa (Table 2) and, since the cyclogenesis occurred over North America, the 17% benefit from this data type must derive either from a downstream effect or, alternatively, from observation of inflowing air, ahead of the incipient depression, off the east coast of North America. Similarly, scatterometer observations of the 10m wind field can only have an indirect impact on this case, and the small impact observed is therefore not surprising.

In this example the ALL OBS and NO OBS control runs have, respectively, the highest and lowest forecast skill. This is not true of all cases, however, some of which have shown negative impacts from some data types (these types would consequently be placed lower than the NO OBS run in the benefit ranking).

4.2 *Finding the 90% subset*

To find the 90% subset we follow a two step process illustrated in Tables 4a-c, again using results from Case 10 as an example. In the first step (Table 4a), a number of model runs are performed introducing one additional data type to the assimilation in each successive run. The first run, is the run (already performed) in which the data type with the largest individual benefit is assimilated (aircraft winds in our example), in subsequent runs data types are added in order of their individual benefit until 90% or more of the ALL OBS benefit is achieved. In our example the first six data types in the individual benefits table (Table 3) are required to exceed the 90% threshold. These data types represent a first estimate of the 90% subset, which is refined in the second step.

In step two we attempt to reduce the number of data types in the 90% subset. This is achieved by removing those types which make the smallest increments

OBSERVATION TYPE USED	RMSE (PMSL)	% OF ALL OBS BENEFIT
ALL OBS	2.34	100
AIRCRAFT WINDS	6.51	50
RADIOSONDE WINDS	6.99	45
AIRCRAFT TEMPERATURES	7.58	38
RADIOSONDE TEMPERATURES	8.28	29
SATELLITE TEMPERATURES	9.34	17
SURFACE DATA	10.13	7
RADIOSONDE HUMIDITIES	10.32	5
CLOUD TRACK WINDS	10.61	2
SCATTEROMETER 10M WINDS	10.64	1
NO OBS	10.76	-

Table 3: Example table of individual benefits of observation types (taken from Case 10, North America 02/11/94). Percentage of ALL OBS benefit is defined as; 100 × [RMSE(NO OBS) - RMSE(OB TYPE)]/[RMSE(NO OBS) - RMSE(ALL OBS)]

to the combined impact until the benefit obtained falls below the threshold of 90%. In our example (Table 4a) the three data types giving the smallest increments as they are added in turn are satellite temperatures (2%), radiosonde winds (7%), and surface data (10%). The result of successive removal of these data types from the subset presented to the assimilation is illustrated in Table 4b. On removing satellite temperatures the benefit remains above 90% of the ALL OBS benefit. The benefit remains above 90% when both satellite temperatures and radiosonde winds are removed (in fact the benefit increases by 1% - suggesting that some conflict between radiosonde winds and the remaining data types). However, on removal of surface data the benefit drops below the threshold to 84%. The final 90% subset therefore comprises aircraft winds, aircraft temperatures, radiosonde temperatures and surface data (Table 4c).

Further runs are performed in order to rank the subset of data types in order of benefit. The data type delivering the largest individual benefit is assigned rank 1; rank 2 is assigned to the data type that delivers the largest increment to the benefit achieved with the rank 1 data type; rank 3 is assigned to the data type which gives the largest increment in benefit to that obtained with the rank 1 and rank 2 data types, and so on. The ranking order for our example is shown in Table 4c.

	OBSERVATIONS USED	% OF ALL OBS BENEFIT
1	AIRCRAFT WINDS	50
2	1 + RADIOSONDE WINDS	57 (+07)
3	2 + AIRCRAFT TEMPERATURES	73 (+16)
4	3 + RADIOSONDE TEMPERATURES	87 (+14)
5	4 + SATELLITE TEMPERATURES	89 (+02)
6	5 + SURFACE	99 (+10)

Table 4a. Step 1: Data types are added to the assimilation in order of their individual impact (Table 3) until 90% or more of the ALL OBS impact is achieved. The impact is measured in terms of the percentage of the ALL OBS - NO OBS error reduction.

	OBSERVATIONS USED	% OF ALL OBS BENEFIT
7	6 - SATELLITE TEMPERATURES	94
8	7 - RADIOSONDE WINDS	95
9	8 - SURFACE	84

Table 4b. Step 2: Data types giving the lowest additional benefit (e.g. satellite temperatures, radiosonde winds and surface) are withheld from the assimilation to see if 90% of the ALL OBS impact can be achieved without them.

RANK 1: AIRCRAFT WINDS
RANK 2: RADIOSONDE TEMPERATURES
RANK 3: SURFACE
RANK 4: AIRCRAFT TEMPERATURES

Table 4c. The final subset is ranked in order of cumulative benefit. Rank 1 is the data type giving the largest individual benefit, rank 2 delivers the largest increment to rank 1, etc.

Examples of both redundancy and synergy between data types can be seen by comparison of Tables 3 and 4c. Radiosonde winds deliver the second largest individual benefit (45%, Table 3), yet are not required in the 90% subset (Table 4c), largely because of redundancy in combination with aircraft winds. In contrast, surface data deliver the sixth largest individual benefit (Table 3), but are ranked third in the final subset (Table 4c), indicating a synergistic effect with either aircraft winds, radiosonde temperatures or both.

Comparison of Tables 3 and 4c also suggests limitations inherent in our assumption that the data type with the largest individual impact will always be a member of the 90% subset. In our example radiosonde winds could probably replace aircraft winds in the 90% subset, since their individual benefit is almost as large (45% compared to 50%, cf Table 3), and the redundancy of radiosonde winds suggests that use of either data type may results in similar adjustments to the model initial state. Changing the rank 1 observation type may, by changing redundancy and synergy effects, result in changes to the remaining members of the subset, or to changes in the ranking order. However, it is clear that if, for expedience, the 90% subset is to be "tied" to one observation type, then the most appropriate observation type is the one that delivers the largest individual benefit.

5. Results

Typically, the major part of the impact is contributed by the rank 1 and rank 2 observations from the 90% subset. We therefore refer to the ranks 1 and 2 as playing key roles in the benefit and the ranks 3 and 4 as playing important support roles. Some justification for this distinction is shown in Table 5, which shows the average increment in benefit obtained by adding observations to the assimilation in order of their rank. Ranks 1 and 2 contribute 86% of the ALL OBS benefit on average, with ranks 3 and 4 incrementing the benefit by a considerably smaller margin than rank 2 (~5% compared to 18%).

OBSERVATIONS USED (11 cases)	AVERAGE BENEFIT (%)	
	Inc	Tot
RANK 1	68	68
RANKS 1 + 2	18	86
RANKS 1 + 2 + 3	04	90
RANKS 1 + 2 + 3 + 4	05	95

Table 5: Average increment in benefit obtained by adding observations in order of their rank.

5.1 *North American Cases*

A summary of the 90% subsets found for the 6 North American cases studied so far is given in Table 6, which shows the number of times that a data type has been included in the subset at a given rank. Only data types that have had at least one inclusion in the subset are shown. Over North America radiosonde and aircraft observations are relatively numerous and the abundance of these data is reflected in their high score in the table. The wind and temperature parts of both data types are included in the subset in at least 3 out of the 6 cases, and play a key role in most instances. The results suggest that the radiosonde and aircraft networks contribute to cases of major impact with similar frequency and that the wind and temperature parts of both systems are of similar importance.

Satellite temperatures show a single inclusion in a supporting role. However, as discussed previously satellite temperatures are not used over land areas below 100hPa (Table 2), and consequently have little opportunity to contribute to an impact source over North America.

Cloud-track winds and surface data both have two inclusions. The inclusions for cloud-track winds suggest a supporting rather than key role, while those for surface data suggest a role intermediate between key and support.

5.2 *Oceanic Cases (North Pacific and North Atlantic)*

Table 7 shows combined results from 3 North Atlantic cases and 2 North Pacific cases. Over these oceanic regions aircraft observations and satellite temperature soundings are most numerous. Aircraft winds dominate the benefit table, contributing in all 5 cases and play a key role in 4 cases. The temperature part of the aircraft observations appears to be much less important, contributing only once and that in a supporting role. This contrasts with the results for North America (Table 6) where aircraft winds and temperatures contribute with similar frequency. One possible explanation for the discrepancy is that the benefit from aircraft temperatures over North America comes most frequently from reports below 500hPa, made in the climb and descent flight phases near airports. There is some evidence from more detailed studies of these cases (Graham, 1995) to support this hypothesis. Low-level aircraft reports are not usually available over oceanic regions where most of the reports are made at cruise levels above 400hPa. The result suggests that, in general, temperature information is more useful if added in the lower rather than upper troposphere.

Despite their use in large numbers over the oceans satellite temperatures only contribute in one case and that in a supporting role. The lack of impact found from this data type may reflect the fact that our evaluations are focused on synoptic scale systems (see section 6.1). Other studies (Eyre et al., 1993) have shown that satellite temperature soundings have their main impact on scales larger than the synoptic-scale. It should also be mentioned that for the cases studied here the soundings were assimilated in terms of retrieved layer-mean temperatures rather than by using variational techniques to make direct use of the radiance information (see Bader, 1995 for a brief overview of the two methods). Eyre et al. (1993) have discussed the greater potential for benefit possible from direct use of the radiance information.

North American cases:
total cases = 6

ROLE	Rank	RsW	RsT	AcW	AcT	SaT	CTW	SFC
KEY	1st	1	2	2	1			
	2nd	2	1		1			1
SUPPORT	3rd			2		1		1
	4th				1		2	
	TOT	3	3	4	3	1	2	2

Table 6: The number of times a data type has been included in the 90% subset at a given rank, North American cases.

Oceanic cases (N.Pacific and N.Atlantic):
total cases = 5

ROLE	Rank	RsW	RsT	AcW	AcT	SaT	CTW	SFC
KEY	1st	1		2			1	1
	2nd			2				1
SUPPORT	3rd	1			1	1		
	4th			1			1	
	TOT	2		5	1	1	2	2

Table 7: As table 6 but for North Pacific and North Atlantic cases combined.

The radiosonde network, with only one key contribution in the oceanic cases, plays a much smaller role than in the North American cases. This clearly reflects the much smaller number of ascents available. No contribution from radiosonde temperatures has, as yet, been found for the oceanic cases.

Cloud-track winds have been included in the subset in 2 of the 5 cases, achieving rank 1 in one case. This potential for playing a key role in the data impacts contrasts with results for North America (Table 6), where cloud-track winds play more of a supporting role. The greater benefit found for oceanic regions must derive both from the larger numbers of cloud-track winds in these regions and from the greater potential for impact associated with sampling a relatively data sparse area.

Surface data have also been included in the 90% subset in 2 of the 5 cases, playing a key role in the impact on both cases. This contrasts with the results over North America which indicate an intermediate role for surface data. The results suggest that surface observations can play a very important role over the oceans where observations of the free atmosphere are scarce (particularly below the main reporting levels for commercial air traffic).

5.3 *The relative benefit of wind and temperature profiles*

Most theoretical work suggests that wind data are more effective for initialising NWP models than temperature data (see e.g. Daley, 1980; Kalnay et al., 1985). Some idealised simulation studies support this conclusion (e.g. Halem and Dlouhy, 1984; Atlas et.al. 1985). Studies of the relative utility of wind and temperature profiles provide insight into the likely impact of proposed space-borne Doppler wind lidar instruments, which could provide global coverage of wind profiles in regions free of thick cloud (e.g. ALADIN, Betout et al., 1989). Such instruments will be expensive to develop compared with passive temperature sounders, and their advantages therefore need to be carefully assessed.

Observing systems that measure both wind and temperature may be used to assess the relative utility of these variables. Such systems will give nearly identical distributions of wind and temperature observations (differences will arise in isolated cases when either the wind part or the temperature part is unavailable or fails the model quality control process). Consequently differences in impact arising from differences in coverage are minimised. The relative utility of radiosonde wind and temperature profiles is compared in Table 8, which shows the individual benefit from these data for the 6 North American cases. Unfortunately interpretation of the figures is made difficult because winds from some radiosonde ascents were inadvertently used twice in the assimilation (this was a result of the practice of transmitting radiosonde wind ascents both as a PILOT message and as a TEMP message). Consequently, the radiosonde wind observations duplicated in this way were effectively used with twice the intended weight. Table 8 suggests that wind data (with twice the intended weighting) provides on average half the benefit derived from all the available data; while temperature profiles provide one third. To assess the effect of the wind duplicates cases 7 (10 Feb 1994) and 10 (2 November 1994) were rerun excluding all the PILOT data (results shown in brackets). For case 7, removing the pilot data had little impact; for case 10 removal of the pilot data reduced the benefit significantly, from 45% to 30%. This latter results suggests that the average benefit from wind data may be somewhat less

than the 50% indicated in Table 8. The marked increase in benefit obtained by effectively doubling the weight of radiosonde winds in Case 10 is a striking example of how the benefit of data is sensitive to the methods used to assimilate it.

It should be remembered that only the impact of the last 15hrs of wind and temperature data are assessed. Theoretical work (e.g., Kalnay et al., 1985) suggests that model fields take longer to adjust to temperature data than to wind data, and consequently the use of a limited period of data may penalise the temperature observations.

As suggested in section 5.2 results on the relative impact of aircraft wind and temperature observations imply that wind data may be more valuable than temperature data in upper levels (i.e. near usual aircraft cruise levels).

CASE		% BENEFIT	
No.	DATE	RsW	RsT
2	26:10:1993	35	54
4	31:12:1993	45	33
5	05:01:1994	56	11
6	10:02:1994	49(51)	56
8	09:07:1994	72	9
10	02:11:1994	45(30)	29
	AVERAGE	**50(33)**	**32**

Table 8: Individual impacts of radiosonde winds and temperatures for the 6 North American cases. Figures in brackets are for runs with PILOT data excluded (the average figure of (33%) is based on results from the Case 10, 02 Nov 1994).

6. Summary and conclusions

Using a series of case studies the benefit of observations to NWP forecasts has been measured according to the number of times they belong to the smallest subset of data types required to achieve 90% or more of the benefit obtained with all the available data. Only cases with a marked sensitivity to initial data have been studied. The conclusions must be considered tentative because of the small sample of cases so far studied. It is intended to complete ten cases for both the North American and Oceanic regions before the next review of results.

The conclusions of the study should be considered in light of the limitations of the method, which are summarised below.

6.1 *Scope and limitations of the method*

Only cases of impact on systems originating over the North American continent and the North Atlantic and North Pacific oceans have been considered. Although this limits the generality of the results it is possible to make inferences for other regions, as is discussed in section 7.

Only benefit to model forecasts of a single variable, PMSL, has been considered. This will clearly influence the perceived observation value. Relative humidity observations, for example, might be expected to rank more highly for forecasts of rainfall than of PMSL (although latent heating effects will clearly feed through to the PMSL fields). The forecast range at which impact is measured (60hrs) will also influence the perceived observation benefit. At a range of about 60hrs developmental changes to the PMSL field will tend to dominate over simple translational changes. Consequently, surface information might be expected to be of lesser importance than data in the free atmosphere which sample important development processes. To summarise, it should be remembered that the observation benefits derived in this study may not be wholly applicable to different models designed for forecasting different variables (e.g. rainfall rather than PMSL) at different space and time-scales.

The method used assesses the benefit of the last 15hrs of data before the forecast, and neglects the value of earlier input to the background field. Consequently, the method favours observations which sample systems that can move or develop substantially on this timescale (e.g. synoptic-scale systems). Observations which sample mainly large-scale systems, which tend to vary little over 15hrs, will have less opportunity to demonstrate an impact. The method therefore penalises the satellite temperature soundings which have low vertical resolution but extensive horizontal coverage, and therefore tend to have their largest impact at scales larger than the synoptic-scale. The method may also penalise temperature observations in general, since theoretical studies indicate that model fields take longer to adjust to temperature data. Furthermore, data impacts on large-scale systems will tend to be overlooked in the case selection procedure, since they will generally be of relatively small amplitude and will therefore exceed the threshold in PMSL differences less frequently than will impacts on synoptic-scale systems.

Results are specific to the UK Met. Office assimilation scheme, and may not always reflect the full potential of the observations. This fact may again penalise the satellite temperature soundings, which have been shown to have more impact when assimilated as radiance information than as the retrieved layer temperatures used in this study.

6.2 *Summary of results for North America*

Observation benefits to global model forecasts of PMSL, based on 6 cases over North America, are summarised below.

- The radiosonde and aircraft networks contribute significant benefits with similar frequency.

- The temperature and wind parts of radiosonde and aircraft observations are of similar importance.

- Surface data (PMSL reports) and cloud-track winds provide the most important support roles.

- Little impact is found from radiosonde humidities (see caveats in section 6.1).

Satellite temperatures and scatterometer 10m winds are considered in the next section. They can only influence systems that develop over North America indirectly or through observing important coastal effects.

6.3 Summary of results for Oceanic Cases

Observation benefits to global model forecasts of PMSL, based on 5 cases over the North Pacific and North Atlantic, are summarised below.

- Aircraft winds contribute most frequently, and considerably more frequently than aircraft temperatures.

- Cloud-track winds and surface data can play key roles in these relatively data sparse regions.

- Little impact is observed from satellite temperature soundings, which contribute only once out of 5 cases and only in a supporting role (but see caveats in section 6.1).

6.3 Summary of general points

- Comparisons of the utility of radiosonde wind and temperature profiles were inconclusive, but suggest that the benefit from wind profiles is equal to or greater than that from temperature profiles.

- Comparison of the relative utility of aircraft wind and temperature observations over North America and over Oceanic regions suggests that;
  - wind data may be of more value than temperature data in upper-levels (i.e above 400hPa).
  - temperature data are of most benefit when added in the lower troposphere.

Observation System Simulation Experiments are needed to provide confirmation of these results.

7. Recommendations for the North Atlantic European area

The substantial benefits derived from the aircraft network over North America suggest that enhancing the aircraft network over the North Atlantic and Europe would yield substantial benefits to forecasts for the European area. Enhancement would be assisted by more widespread use of automatic observation and transmission technologies. Reports over Europe should include observations made during climb and descent phases.

High resolution data from below aircraft cruise levels is badly needed over

the North Atlantic. The potential value of such data may be inferred from the substantial benefit obtained from aircraft temperatures over North America, much of which appears to derive from data in low-to-mid levels. Our preliminary results imply that TOVS data, which sample these levels, are of limited utility in resolving rapidly evolving synoptic detail (though they may be important in maintaining the general quality of the model background). High resolution soundings will not be available before 2000, when the IASI (Improved Atmospheric Sounding in the Infra-red) instruments are scheduled to become operational (though the ATOVS data, scheduled to come on line in 1996, will provide better moisture sounding and improved coverage in cloud). The timescale for global coverage of wind profiles, as might be provided by space borne Doppler wind profilers (e.g. ALADIN), is more uncertain but probably lags IASI by 5-10 years.

In the meantime improved observation can be approached using conventional systems. Our results show that in the absence of good coverage in the middle to lower troposphere, surface data can deliver important impacts. Increasing the coverage of surface information (buoys, ships etc) might be worthwhile as an intermediate step to obtaining more extensive observation of the boundary layer and free atmosphere.

The feasibility of an "adaptive" observing system should be investigated. Such a system would likely be based on dropsonde instruments, possibly launched from unmanned aircraft, and could provide high resolution profiles of the middle and lower troposphere in regions where errors in the model background are growing rapidly. Objective techniques (e.g. the error breeding techniques described by Toth and Kalnay (1993)) can be used to identify such regions. An adaptive observing system would therefore target regions where data are most needed and could prove very cost-effective. The above recommendations are summarised below.

- Acquire more aircraft data over Europe and North Atlantic.

- Consider deployment of more surface observations in the North Atlantic to help compensate for the current lack of high resolution data in the low-to-mid troposphere.

- Investigate the feasibility of an "adaptive" observing system designed to target regions where errors in the model background are growing most rapidly.

Acknowledgements

We would like to thank Bob Lunnon, Andrew Lorenc, Mike Bader and Roger Grant for guidance at various stages in this study; and Stuart Bell, Bruce Ingleby, Colin Parrett and David Robinson and Mussadiq Ahmed for help and advice on the assimilation aspects of the work.

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